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Chapter 1
Growing Smart Cities

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Abstract As the world's population becomes increasingly urbanised the problems of building sustainable cities also grows. Using Susan Stepney's response, "Mighty Oaks from Little Acorns Grow", to a science fiction story by Adam Marek titled "Growing Skyscrapers", this chapter looks at what a living city of the future might look like, and how that might solve some of the problems of the control and development of cities. There is a long history of the application of systems thinking, cybernetics, and complex systems and the growth and control of cities. However, many problems still remain in the deployment and applications of these frameworks and methodologies, and in the potential consequences of their use. However, perhaps many of these could be solved by the development of a *living city*.

1.1 Introduction

The control of the growth and development of cities presents a significant challenge to their human designers. The services that a city needs to provide for its inhabitants, or the services that the inhabitants require from their city, will radically change between the moment of its emergence as a group of buildings and the point at which it becomes recognisably a city (which is not a point of completion, it is reasonable to say that cities are never *finished*). This is true of cities that are planned, but even more so of cities that just *happen* (which is historically at least a significant proportion of them). A city exists on a different temporal scale to it's inhabitants, and the infrastructure it provides is in a constant state of revision; a process without end.

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This constant evolution might, if not somehow regulated, not produce positive change. The idea of the evolving city and how this can have a negative impact on a city is a central point of Jane Jacobs' 1961 book, *The Death and Life of Great American Cities* [21]. Jacobs' work tells a story of how uncontrolled suburban growth (often referred to as sprawl), coupled with the rise of the automobile and the parallel death of public transport, is killing American cities. The functionality and utility of a city as a place to live is being eroded by suburban growth. Although the city is growing in terms of its housed population, the infrastructure (transport, utilities etc), green spaces, commercial space, is not developing in step with the increasing population. Some took this as a argument for centralised planning; top-down approaches that could introduce order into the sprawl. However Jacobs is perhaps arguing, and even more so in later work, for more bottom-up decentralised change [23, 22]. The notion of urban sprawl suggests that the required feedback mechanisms and regulation required for positive growth are not present, and if decentralised feedback systems are put in place the city will adapt to support its growth. One view of what is being described here is a self-organising complex system adaptive system, where the growth of that system are regulated by internal feedback systems.

Complexity theory describes a relational model of systems, where a system of interest can be broken down into parts, and the interactions between those parts. The behaviour of the system is then an emergent property of the parts and their interactions (often these systems are self-organising). Complex systems often have a number of common features. They can adapt their environment and therefore have the capacity for change, and are able to learn. This is often linked with the idea of system memory, the current state of the system is a product of past sates, and future states are influence by the current state. Complex systems also demonstrate resilience, and therefore are able to respond to changes in their environment without failure. However, somewhat counter to this, their behaviour is also non-linear, and therefore a small perturbation could produce no response, a proportionate response, or perhaps produce massive changes. For a more in depth characterisation of complexity and the features of complex systems see Manson (2001), Vicsek (2002), Kauffam (2006) and Stepney (2018) [27, 43, 24, 36].

Cites can therefore be described as complex adaptive systems which are subject to constant change, and the functionality of the city is an emergent property of all the different interacting parts within it [2, 3, 5]. Or put a different way, the city itself is a manifestation of the interaction of the parts. It is an emergent property of all the people, buildings, transport systems, and businesses within it. How cities are governed therefore presents a significant challenge to their inhabitants. Understanding and controlling the processes of change and revision is difficult and hard to manage, as it is hard to locate agency in complex systems in order to make interventions [38]. In the context of a city, it is not as simple as the humans in the system being the sole agents of change. They are components of the larger complex system, but are not the only drivers of change. Therefore the human parts of the city might be (or rather, are quite likely to be) unable to see (or predict) the full consequences of their actions within the larger system that is the city. Other processes need to be recognised and responded to, as demonstrated by the (unregulated - where by regulation we mean by feedbacks within the system, more in the sense of regulatory feedback in biological systems) city expansion in America that produced the sprawl. This highlights another difficulty of complex systems; where does one system end and another begin. Where does one draw a boundary between one system and another, or one city and another. Often system boundaries are drawn for pragmatic reasons, rather than because there exists in reality a definable boundary, and it is understood that there is flow across that boundary (the boundary is fuzzy). Problems of nestedness, embeddedness, and boundary determination also apply to cities [6]. Where does a city end? Is it before or after the sprawl, and what about when one city merges with another? Where ever the boundary is drawn, people, goods, policies, and ideas will flow across the limits of a city, contributing to the city environment.

We know from the governance of complex systems that it is hard to have sufficient knowledge of a complex adaptive system to be able to make adjustments, and have an understanding of what the impact, across the system as a whole, will be [24]. Changes to one part of a system could produce emergent behaviours elsewhere in the system [33], which may even result in failure [17]. In a city for example, changes to a road system in one area could produce traffic problems or pollution in another. Or the development (or redevelopment) of land could have similar unexpected effects to other aspects of the city's infrastructure. A lot of these problems could be due to the human mediation of the response of the city to its changing environment. Human interference in the evolution or growth of the city. If new housing is needed, it is humans that have to sense the need for the housing, determine where it should be positioned, and implement the change. A process that can often be more politically driven rather then need driven. It is not an organic response by the city to a perceived need for additional capacity for housing in a particular region of the city (change driven by internal feedbacks or regulation). The same would be true of any other necessary change in infrastructure. The human inhabitants would have to perceive the need for the change, and then enact it on behalf of the city. As cities cannot *grow* on their own, adapting their internal dynamics to the environment, like a biological organism is able to.

Frameworks and methodologies have been proposed as to how a complex systems could be steered or governed, or how desirable attributes could be maintained and enhanced. In their paper *Engineering Emergence* (2006) Stepney and Polack describe how the resilience (fault tolerance, robustness, and adaptability) of systems is often linked to a system's emergent behaviour, and therefore it would be advantageous that when designing systems, like cities, if emergence could be engineered in [37]. Later work explores what the features of a design framework might be, suggesting that in the future we might have frameworks to build large scale engineering projects that exhibit desirable emergent properties [42]. This chapter will investigate the concept of a growing, living, smart city. A living city would need to demonstrate the properties of emergence, including fault tolerance, robustness, and adaptability. Beyond that, could a living city sense the requirements for change itself and enact those changes, and what might the consequences of allowing a living city evolve to adapt to those perceived needs be?

1.2 Cities as Complex Systems

Cities are themselves complex adaptive systems, where one element with the possibility of producing change with in them are the humans. The human inhabitants are part of the system, and their interactions with the other parts can alter the emergent global behaviour of that system, but not always in ways which are expected or desired. Additionally cities are human infrastructure projects, designed by humans to provide for the needs of their inhabitants, both domestic and commercial. However this does not necessarily mean that cities lack any agency of their own, or that the inhabitants are the only agents for change within a city.

Aspects of complexity theory and complex systems models have been applied to the problem of growth of cities in a number of areas, and cellular automata one example of the application of ideas of self-organisation and emergence to city growth and change. Cellular automata are an example of a complex system, which through the application of a simple set of rules can demonstrate complex phenomena [47]. They are often modelled as cells on a two-dimensional grid which respond to their environment by either persisting, dying, or reproducing, and in doing so create changes in the environment. Information from the environment is communicated to the cell which determines its fate, in a process that was thought to be analogous to the development of biological cells [41, 44]. Perhaps the most famous cellular automina is Conway's game of life [15, 16]. The game has the following rules:

1. Any live cell with fewer than two live neighbours dies, as if by under population.
2. Any live cell with two or three live neighbours lives on to the next generation.
3. Any live cell with more than three live neighbours dies, as if by over-population.
4. Any dead cell with exactly three live neighbours becomes a live cell, as if by reproduction.

The environment is seeded with a number of cells and the generations of cells are produced by applying the rules simultaneously to all the cells in the environment. Each generation is therefore a product of the preceding one. These simple rules define the relationships between the parts of our system (the cells) and are capable of producing all manor of complex behaviours that could be difficult, or perhaps impossible, to predict from the rules alone. However, these behaviours reveal themselves when the game is played.

Where cellular automata have been applied to the modelling of cities is in the possibility of defining distributed rules that describe how one area of a city might develop in the future based on its own state, and the state of the surrounding areas. Models follow the basic principle that an area, or neighbourhood, of a city changes in response to its current state and the state of the surrounding neighbourhoods. One could imagine that this might be true to a certain extent, gentrification or urban decay do seem to spread through cities, however this is unlikely to be simply due to neighbour effects alone. Such neighbourhood, or city area, models can also demonstrate emergent properties, where groups of cells form stable or quasi-stable neighbourhoods, for example 5x5 or 3x3 groups of cells that maintain some sort of property over multiple generations [45, 3, 34]. Much like how some city areas can maintain a character over long periods of time. One of the more significant limitations of cellular automata as a model of city evolution, which we alluded to already, is that they are only really designed to model neighbour effects. It might be that some of the feedbacks operating in cities cannot be modelled in this way.

Other complex systems models of cities have been built with agent based modelling, where an agent is "a part of the environment that senses that environment and and acts on it, in time, in pursuit of its own agenda and so effects what it sense in the future" [14]. Agent based models map well to complex systems as the agents describe the parts of the system, and the system behaviour is a product of the interactions between the agents. Agent based models of cities (or other aspects of society) extend from large scale, even multi-city models, down to models that work on the scale of individuals, demonstrating the capacity for modelling at different scales [40]. In order to investigate a problem, or the possible outcome of an intervention, aspects of the city could be captured by agents and relationships between those agents and the environment defined. The simulation of the model then allows for the testing of hypotheses about the cause of the problem, or the possible different outcomes of the intervention. However one difficulty is that agent based modelling still presents a challenge in terms of computational capacity [10]. Weather it is possible to design and implement agent based models that could be used to model and understand a whole city, or network of cities, remains to be seen. An appropriate level of abstraction would also need to be arrived at for it to be useful tool.

1.2.1 The Cybernetic City

The models presented in section 1.2 demonstrate how complex systems modelling approaches could help us understand that the cities that we have. The intention is that this improved understanding should allow for better interventions to be made, however knowing where and how to intervene in a complex system is very difficult. It is worth mentioning here the (trans)discipline of Cybernetics. Cybernetics was intended as the "scientific study of control and communication in the animal and the machine" [46]. Studying something as a cybernetic system would provide insight into how to steer, or govern, the system. Precise control might not be possible, however the system could be navigated in a desirable direction. There were attempts to use the principles of cybernetics to design self-regulating control systems for real-time planned economies, including work by Viktor Glushkov [19, 1] and Stafford Beer's Cybersyn project [30, 12], and urban systems more generally [29]. More recently the idea of the *adaptive city*, a city that is able to adapt to the day to day changes in conditions in cities, is been explored in the context of cybernetics [18].

Beer's Cybersyn is an example of a dashboard control room that was intended to allow for the operation and control of the Chilian economy [30, 12, 31]. One potential problem with such dashboards is that they assume that such control is even possible, and could perhaps inspire thoughts of top-down control system in their users (if not their designers). Dashboards (in general) may suffer from the assumption that somehow the complexity of an economy (or even a city) can be reduced and displayed on a dashboard in such away that it could be used to understand, and then intervened in, such a system [4]. Dashboards, or control centres, are still being built that are intended to manage a city, and make sense out of the myriad indicators that could be constructed from different data sources. One problem with this is the central assumption that management of such a complex system is possible, or they might inspire a belief in a level of management that is not possible. Another criticism is that the construction of control rooms and dashboards potentially forgets that the data that is chosen to be collected is likely to be socially constructed and probably biased in numerous ways. What the designers choose to feed into the control room or dashboard is likely to influenced by their own internal biases, a difficult trap to avoid. Furthermore, the use of dashboards could potentially hide the role of socially constructed data and therefore present an essentially false view of what is actually happening [25].

A criticism therefore of implementations of cybernetic theory, and more so the often accompanying related dashboards, is perhaps that they embody an external control system that takes information in from a system and then outputs changes to that system. Despite the work of von Forester (see also Mead (1950) and Bateson (1952) [32]) on second order cybernetics that sought to firmly embed the observer in the system [13]. Therefore also forgetting, perhaps not intentionally, some of the features of complex systems. The builders of such systems could even be aware of the need for the control room to be 'part of the system', however the dashboard still manifests physically as an external control room for the collection and presentation of data. Separating the control room and its occupants from the rest of the city. Inviting decision making processes that have at their heart simplistic and reductionist thinking processes and evidence, even if that was explicitly not the intention [7].

Therefore perhaps a change in the process of *thinking* is also required. Caves and Teixeira de Melo (2018) propose the concept of gardening to develop "a relational framework for complex thinking about complex systems" [8]. They evite the potential user of the framework to think about "what are the things I need to think about when I think of change in the system of interest?", and "how do I need to think about them, and the relations between them?" [8]. Embedding the relational aspect of complex systems into the thinking, and complexity into the thinking itself. For a city to be viable as a living system the relationships between the parts would need to be captured and understood, otherwise the city would not grow as intended, and new frameworks for thinking may be needed to achieve that.

1.3 Growing Skyscrapers

In the 2014 volume, *Beta Life Stories from an A-Life Future* [20], Susan Stepney responds with (*Mighty Oaks from Little Acorns Grow*) to a Adam Marek's chapter *Growing Skyscrapers* [20, pp.41-62]. The story presents a future where massive skyscrapers are not built by an untidy process of construction by humans, but rather they grow in place from a seed. The seed grows and develops gradually into a building, taking in from the environment the raw materials required to construct the different components of the building. The walls, internal structures, electrical infrastructure, and its foundations, develop and expand in a manor not unlike a plant such as a tree. A tree develops foundational roots that provide stability and water, builds a circulation system for transport, and a network of branches that support leaves which in turn collect sunlight and CO2 from the air. All requirements to support the growth of the tree.

Three protagonists in the story are investigating a rouge building, "The Jetty", developing as a massive jetty stretching out into the sea from the coast. A growth stemming from the unauthorised planting of a seed, "stolen technology". We encounter them measuring the foundation, "roots", of the building to check that their size will support the building, and its inhabitants above. Essentially checking that the internal feedbacks in the complex system are correctly regulating the development of the foundations. With a view to whether the building is safe. We learn that "The Jetty" has grown chaotically, without "the guidance of a trellis or an architect", or perhaps a gardener [8].

The story also follows two inhabitants of the building, as they live (and grow) in their growing habitation "pod", *living* quarters that develop and mature as the building does. There is a symbiotic (or perhaps parasitic, it is not clear) relationship between the building and its inhabits. The building produces an edible sap that they can eat, perhaps the building can draw nutrients from the waste products of the inhabitants. The building may benefit in other ways from habitation, care from humans in the event of disease, or maintenance and the repair of injury should the building suffer damage, however this isn't clear. Stepney, in the response, discusses the concept of gardening of complex systems (a concept also discussed as a model of thinking in Caves and Teixeira de Melo (2018) [8]), to encourage development of the system in a particular way. Perhaps gardening of a growing skyscraper could constitute symbiosis, as the removal or pruning of vulnerable or injured sections to prevent further damage or disease, or the control of pests, is of mutual benefit. The inhabitants of a building would benefit from increasing the longevity of the building, and utility of the space, through pruning (or gardening more generally), and the building benefits from a live in maintenance crew and in a sense an immune system (as humans acting to prevent disease from inside the building could be viewed as such).

The book ends with what appears to be a an attack on the building. There are hints in the story that the *owners* of the technology that is the growing building, have also developed a way to restrict or control the use of the technology. A girl sits in her pod, her developing space for habitation, when an large black beetle lands on the window, soon joined by another, this is something new that has not been seen before. The implication is that this is a *pest* sent by the *owners* to destroy the building. Reminding us that a sophisticated new living technology would be vulnerable to a new form of sophisticated living attack, both biological control developed by humans but also hostile acts or perhaps other organisms that evolved to take advantage of a new environment.

1.4 The Living City

The concept of the living city would be a natural progression of that of a living skyscraper, which are in many ways are small cities in their own right. The chapter *Growing Skyscrapers* talks about enormous buildings over a mile high, which would presumably have many thousands of inhabitants and both living and commercial areas [20, pp.41-62]. There is no reason why this would have to be the only model for a *living* environment.

A living city could also resemble more the cities of today, that are often a mixture of buildings of different sizes and uses. These could perhaps all be part of one massive living city structure, that would spread over the entirety of city limits providing all the different types of infrastructure required by their inhabitants. Perhaps the nearest living example of this would be the Humongous Fungus, which is thought to spread over an area of as much as 4 square miles [35]. Armillaria ostoyae fungi can exist over very large spaces and present a variety of different structures, including underground networks for nutrient collection, with fruiting bodies (mushrooms) that sprout up out of the ground for the purpose of reproduction. These massive fungi that spread over very large areas are considered to be a single organism.

The advantage of a single city organism is that information about the environment could be collected an distributed around the entire city with ease. Allowing the feedbacks that change the city to work over long distances, as well as short ones. The biological processes that control the growth of organisms like fungi are coordinated but decentralised, demonstrating other features that would be desirable in a living city as it would negate the need for any central control system or dashboard. One potential problem would be that one organism would need to provide all the different types of structure and infrastructure required. Encoding this into a single genomic DNA blueprint might prove to be a challenge, even for the geneticists of the future. Perhaps it might be better to think in terms of a symbiotic ecosystem of multiple organisms, including the human inhabitants, co-existing to produce the living city. The cities would be a decentralised, multi-organism, ecosystem of mutually beneficial symbiotic relationships. Designed to display the required emergent properties that a city would need; fault tolerance, robustness, and adaptability.

1.4.1 Growing a Smart City

If we put to one side the science fiction of a literal *living city* and look more at developing and improving what we have then the the concept of a living city still has a lot to offer. Excepting that a city currently grows as a consequence of the activity of their human inhabitants, but moving away from the inhabitants as the only agents of change. In section 1.2 and 1.2.1 we explored how complexity and cybernetics can be applied to the governance and planning of cities, but what if the city itself could regulate its growth? This would make a city more of an ecology, a living entity (or entities) in its own right that can grow and adapt in response to feedbacks from the organisms that live within it.

There are a number of potential problems with moving agency away from the humans and more towards the adaptive system as a whole. By which, no single part of the complex system should have ultimate control of how the system develops. Instead the system should be allowed to grow and develop in response to the multiple feedbacks within the complex system. This might not be possible in situations where there are self-interested parties that do not want to relinquish their control over how a city develops, perhaps out of fear that their own situation in terms of living standards might be negatively effected somehow. Loss of control in this way is also not condusive with our current modes of living, which are essentially fairly static.

One constraint on the development of *living cities* would therefore be that some of the features of living systems are not desirable for human systems, such as death or failure. In ecosystems parts of the system are allowed to fail, organisms die and make way for other organisms (or provide resources to other organisms). In a living city it might be necessary for parts of it to die back, and be replaced with different structures as the city grows. Or areas of the city might change and adapt around its inhabitants, essentially changing their position in the greater whole. This happens in cities already, old parts are taken down and replaced, and much of this type of change would be normal to some inhabitants of today's cities. However, others might not welcome a reduction in their own power to control and shape a city in order to allow it to adapt better for the needs of its inhabitants as whole. In a living city a mechanism would be required such that this type of change was seen as normal, and people having to move because their current housing was dying so it could be replaced with transport infrastructure was seen as a necessary adjustment due to the changing nature of the city in that area. A reality that many face already.

As with large decentralised living organisms, like the Humongous Fungus, biological systems have perhaps also developed huge growing smart cities before us. Researchers discovered a massive city of termites, roughly the size of Great Britain and as much as 4000 years old [28]. The complex of 200 million interconnected termite mounds perhaps demonstrates many of the features we would like for our own growing smart cities. It is self-organisation and decentralised on the city scale and also at the level of individual mounds or buildings [48], and has remained stable for for a very long time. Proving that we have a lot to learn about the organisation of our own societies.

1.5 Conclusion

The concept of a city as a living system at this time seems distant to the point of far fetched. However, thinking of cities as living is less so and has its uses. Cites, as they exist today, are human impositions on an environment, radically changing the environment in order to serve the purpose of human activity. Humans impose urban structures on the environment and in doing so cause significant damage. Swyngedouw's (2006) paper, *Circulations and metabolisms: (Hybrid) Natures and (Cyborg) cities*, describes how the "intermingling of things material and things symbolic produces a particular socio-environmental milieu that welds nature, society and the city together, often through many layers of networked technostructures (like pipes, cables, relay stations, logistical apparatuses and the like)" [39]. The city is an assemblage, or complex system, of parts and their interactions in space. However, Swyngedouw goes on to say that "[a]lthough the city turned into a metabolic vehicle, the rift between the social and nature became in fact rather deeper than ever engrained in the urban or modern imagination" [39]. Suggesting that the function of the city has a place of human habitation has become increasingly divorced from nature. Re-imagining the city as part of a living ecology, that is itself alive, should motivate us to change the relationship of cities with the rest of the environment (and perhaps our interactions with the environment in general). A living city would need to co-exist with the rest of its environment to be sustained by it, not be an imposition and source of damage in terms of toxic wastes and other pollution. Moving further in this direction would also improve the resilience of the cities to change and allow them to adapt to the changing environment around them. We should develop cities that are part of the environment, not an imposition on it.

Current development of smart and eco-cities has been criticised for producing cities that are not connected, rather they are desperate parts that do not efficiently or effectively work together, or exhibit the desired sustainability. A reality that is at odds with the goals of smart and eco-city projects [9]. Cugurullo's (2018) paper, *Exposing smart cities and eco-cities: Frankenstein urbanism and the sustainability challenges of the experimental city*, frames this in terms of *Frankestien urbanism* "which draws upon Mary Shelleys novel as a metaphor for unsuccessful experiments generated by the forced union of different, incompatible elements" [11]. Current development of smart cities is not being developed using a complex thinking approach [8], and the result is a mess of loosely connected parts that will not produce the change that was intended.

Richard Young's (2006) paper, *Cybernetic Beunos Aires* captures the changing nature cities more through changing culture [49]. Where he describes tangos that lament the creation of an "urban dystopia", including "the impact of the shift from human to machine-mediated contact" and surveillance, both are a likely consequence of the implementation of the goals smart-city projects. In order to control a smart cities data is required from sensors, this has significant potential downsides, including the transforming of citizens into sensors and the enhanced surveillance that comes with that. The technologies deployed to control smart cities could therefore be used to control society, as well as the city which houses it [26].

A truly living city would not require such oppressive top-down control systems, instead control would be decentralised and perhaps impossible to locate. It would be embedded into the system as a whole, woven into the connections and relationships. Interventions would have to be made using the framework of complexity thinking if they are to be successful, ot avoid a return to simplistic and reductionist thought processes and decision making. However significant challenges remain, not least a radical re-framing of our own role within a city, if we are ever to inhabit such a living city.

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